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Abstract

On the toroidal magnetized plasma discharge ToriX, a collective light scattering device has been set to investigate plasma turbulence and transport. The light scattering intensity provides a measurement of the static form factor, at the scale of the scattering wave number k. The form factor is found to be very large, five to nine orders of magnitude above the equilibrium level. As a function of the k wave number, an exponential decay is found instead of a scaling law. This implies long range spatial correlation. When a vertical field is added to the horizontal toroidal B field, a significant decay of the form factor intensity is observed.

The scattered light time correlation is investigated as a function of **k**. It is interpreted with the help of a model of brownian type of turbulent motion (the Ornstein correlation). According to this model, the signal auto-correlation function is expected to be:

$C(\tau)=A \exp\{-k^2 l_c^2[1-\tau/\tau_c - \exp(-\tau/\tau_c)]\}$,

where τ_c and l_c are the turbulent motion correlation time and length resp. . A best fit of the experimental data with this model correlation provides τ_c and l_c (and possibly $D= l^2_c / \tau_c$, a turbulent diffusion coefficient). Detailed investigations show this method provides a good measurement of the turbulent velocity ($u=l_c / \tau_c$), and some of the non-gaussian properties of the plasma turbulent motion.

Introduction

Turbulence and transport phenomena can be remotely investigated in plasma devices by collective light scattering. This is true in tokamaks[2,3] as well as in space[4,5] plasmas. The scattered (electric field) signal amplitude and time correlation are expected to be[6]

$$\langle s(t)\cdot s^*(t+\tau)\rangle \cong S(k)\cdot \langle e^{ik\delta(\tau)}\rangle \qquad \text{Eq.1}$$

If n(k) is the electron density spatial Fourier transform at wave vector k, S(k) is the form factor at observed wave vector k,

$$S(k)= \langle | n(k)^2 | \rangle/(n_0V) \qquad \text{Eq.2}$$

where n_oV is the total number of observed electrons,

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$\delta(\tau)$ is the displacement of a given fluid element in a time τ ,

$<e^{ik\delta(\tau}>$ is the statistical characteristic function, i.e. the Fourier transform of the random displacement $\delta(\tau)$ probability distribution at time τ, $P(\delta | \tau)$

$<e^{ik\delta(t}> = \int e^{ik\delta} P(\delta | \tau) d\delta$ Eq.3

Both the form factor and this plasma turbulent motion statistic should be retrieved from the signal of a single scattering diagnostics. Implementing such a method, the plasma form factor and turbulent motion statistics are investigated in a laboratory magnetized plasma.

The Torix and Fremir devices

The experiment is conducted in "Torix", a toroidal magnetized discharge plasma, of 0.6m (large) and 0.1m (small) radius. The toroidal B-field intensity is 0.17 to 0.36 Tesla, the Argon plasma density is 10^{17} m^{-3} and the electron temperature is 2 eV. The plasma configuration is not a stable one, the density fluctuates at a large rate in the kHz range of frequency[7]. An additional uniform B-field component of about one mT along the main (vertical) torus axis, can be applied.

This plasma is observed by the infrared collective scattering device "Fremir", using a 2 Watts DC, CO_2 laser (λ=10.6μ) with an 11 mm waist. The primary beam crosses the plasma device equatorial axis along a vertical cord. The scattered light, emitted at an angle of 1.3 to 3.3 mrad with respect to the primary beam axis, is collected, together with an L.O. beam, on a nitrogen cooled photodiode. The scattering analyzing wave vector **k** is along the main radius (across the toroidal B field), and its wave number ranges from 770 to 2000 rad/m. From a quadrature heterodyne detection circuit output, the amplitude and phase of the scattered E-field are recorded as time series.

Form factor and turbulence amplitude

By calibrating the detection chain, the scattered signal intensity provides a measurement of the "Form factor", S(k). For uniform plasma, the form factor is unity whatever is k. This is not the case in a turbulent plasma. This is illustrated in Fig.1, where the form factor (blue line) is plotted against the scattering wave number k (semi-log scale). The form factor intensity is large (from 10^9 down to 10^7); it decays exponentially as k increases from 800 to 1800 rad/m, with a characteristic decay length l_p. This range of scales is comparable to or slightly larger than the ion Larmor radius ρ_{ci} at room temperature ($\rho_{ci} \approx 0.4$ to 0.3 mm), i.e. $k\rho_{ci} \leq 1$. The decay characteristic length l_p is 4.6mm, about ten times ρ_{ci}.

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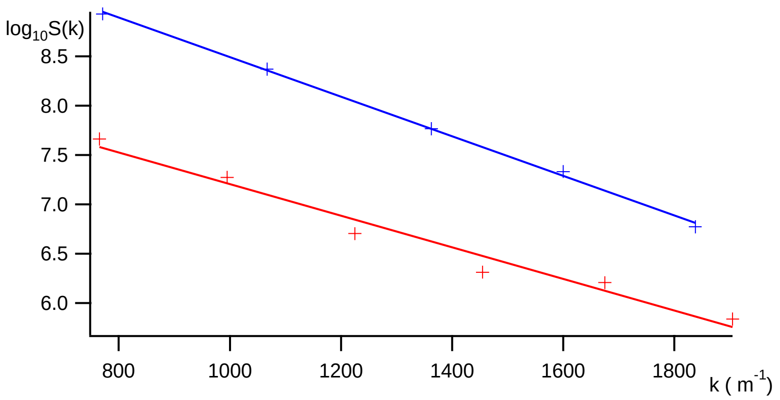

Figure 1

Form factor as a function of wave number (semi-log scale). Top: form factor in a purely toroidal B-field (B=0.28T); it is seen as an exponential function of k. Bottom: form factor for the same plasma parameters except for the addition of a weak vertical fiel B_V=1.8mT; the form factor is decreased by a factor of 13.

If a small vertical B-field (1.8 mT) is added, the form factor decreases by one to two orders of magnitude. This is shown as the red line in Fig.1. This decay is a consequence of a possible electron helicoidal vertical motion, whereby the ∇B vertical charge separation can be compensated, thus attenuating the plasma outward relaxation.

Dynamical form factor and turbulent motion

- The scattered E-field time correlation is the statistical "characteristic function" of the random displacement $\delta(\tau)$ of any fluid element in a time τ,

$$C(\tau)=\langle e^{ik\delta(\tau)}\rangle \qquad \text{Eq.4}$$

The Ornstein model correlation is obtained when $\delta(\tau)$ is a random variable with gaussian probability distribution[8],

$$\langle e^{ik\delta(\tau)}]\rangle = \exp[-k^2\langle|\delta(\tau)^2|\rangle/2] \qquad \text{Eq.5}$$

where $\delta(\tau)$ can be obtained from the correlation length l_c and the correlation time τ_c of the Lagrangian velocity,

$$\langle|\delta(\tau)^2|\rangle=l_c^2[1-\tau/\tau_c - e^{(-\tau/\tau c)}] \qquad \text{Eq.6}$$

For long time ($\tau>\tau_c$), the rms displacement increases linearly at the usual diffusive rate $\langle|\delta(\tau)^2|\rangle\approx (l_c^2/\tau_c)\tau$, and the signal time correlation function is exponential. At short time instead ($\tau<\tau_c$), $\langle|\delta(\tau)^2|\rangle$ increases at the rate of the turbulent velocity u_t ($u_t = l_c/\tau_c$), and the time correlation is gaussian.

- A series of scattered signal time sequences have been recorded in the same plasma (B_T=0.336T, B_V=1.8mT) with different scattering k-vectors. A frequency spectrum is calculated from the complex signal; from it the no-plasma signal spectrum is subtracted.

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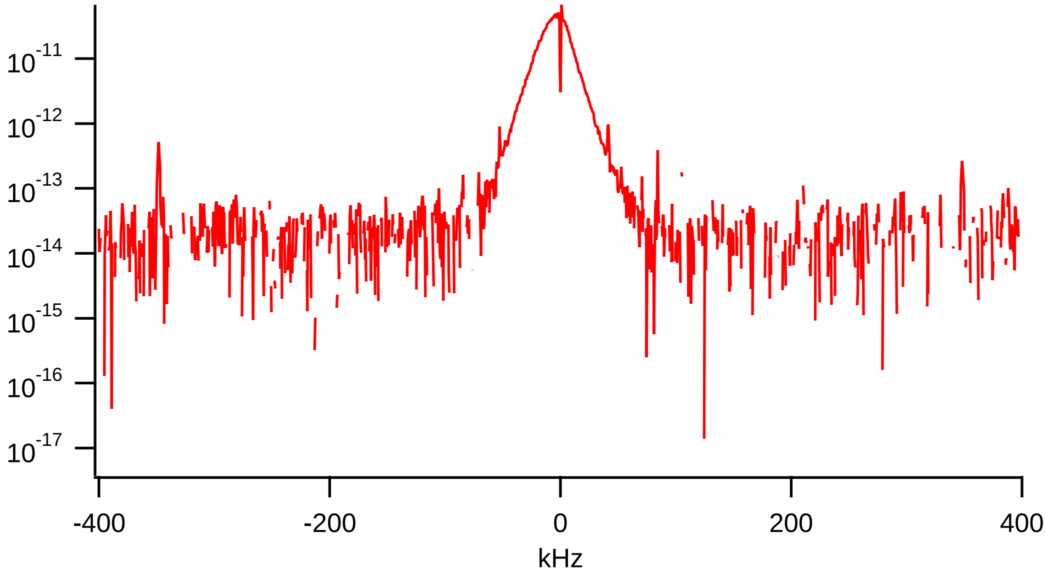

Figure 2

Scattered signal frequency spectrum from a magnetized plasma. The wave vector is k=1240 rad/mm; the toroidal B-field is 0.28T, with an additional vertical B-field of 1.8 mT. The spectrum is symmetrical and the signal dynamics reaches 40db.

The time correlation can be obtained as the spectrum Fourier transform. Before this transformation, a short scale smoothing is effected to erase the low frequency band-reject filter hole near the zero frequency. Six such experimental correlation functions are shown in Fig.2 (black dots), for increasing values of k from 770 to 1970 rad/mm. Each of them is further fit with the Ornstein correlation function (Eq. 5 and 6), where the correlation time and length are optimized. The best fits are shown as the red lines. An excellent agreement is found.

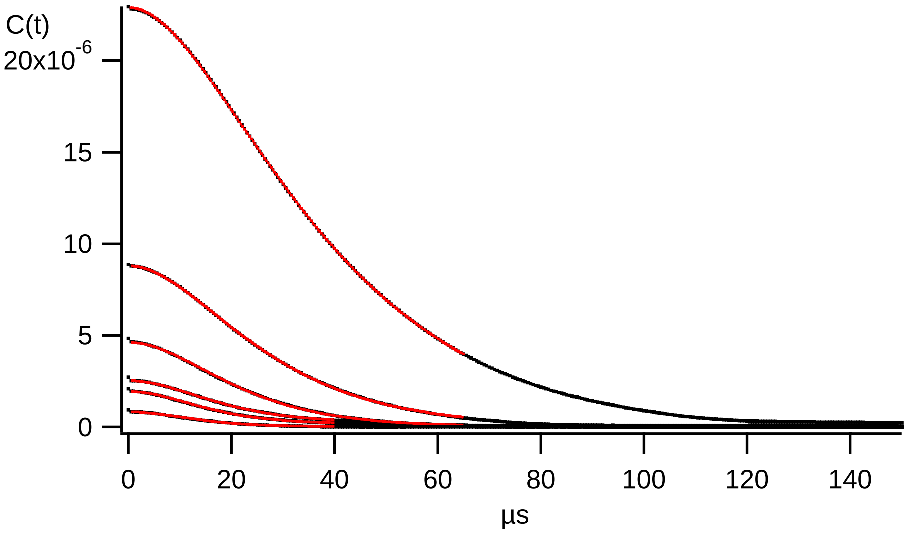

Figure 3

Signal time correlation function, for different wavevector. Black dots: experimental values; red line: the Ornstein model equation best fit. Plasma toroidal B=0.336T, vertical B=1.8mT; the wave number is (from top to bottom) k=770, 995, 1240, 1480, 1730, 1965 rad/mm.

From such a fit as in Fig.3, the two parameters u_t (turbulent velocity) and l_c (lagrangian correlation length) are extracted. The velocity u_t is found to be the same (58m/s ± 3%) whichever is k, as expected. But the correlation length l_c is found to change with k in such a way that kl_c is almost constant, and near to one (kl_c =0.9 ± 20%). If in addition one is willing to extract a diffusion coefficient ($D= u_t\, l_c$), it is found to decrease as function of k. A similar analysis can be made on the signal frequency spectrum, where the fit is done on the Fourier transform of Eq.5; this analysis provides close values for the fit parameters[9].

These observation contradict the gaussian displacement probability hypothesis and its consequences (Eq.5 and 6). To check this in more details, we plotted the log of the signal correlation as a function of k, for different times (Fig. 4a and 4b). Eq.5 predicts this log to be proportional to k^2 at any time. This behavior is indeed observed at short time (τ=2.5µs, Fig.3b), but not at longer time where instead the log function is found to be proportional to k (Fig.3a).

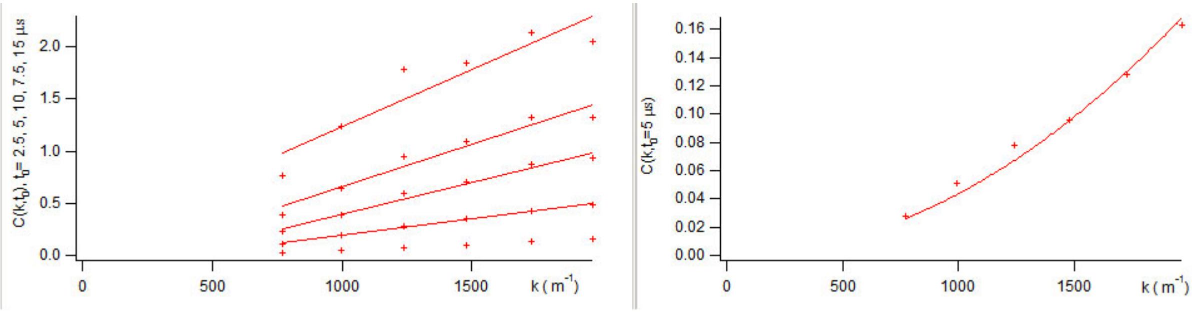

Figure 4

The opposite of the signal correlation logarithm as a function of k, for fixed times (t_0= 2.5, 5, 10, 7.5 and 15 µs). It is seen as increasing linearly with k, except at short time (t_0=2.5 µs, figure on the right at an enlarged scale) where LogC(k) increases as k^2.

If the displacement probability is not gaussian, it remains that the signal time correlation is the Fourier transform (with argument k) of the displacement probability distribution $P(\delta\,|\,\tau)$ (Eq.3) : from the signal correlation it is possible to extract information on $P(\delta\,|\,\tau)$. As shown in Fig.4a, the probability FT is an exponential of k with a negative argument. The displacement probability distribution is provided by an inverse Fourier transform. Performed on such an exponential function of k, this transform provides $P(\delta\,|\,\tau)$ as a Lorentzian function of the distance δ. This is a very long range extending space correlation. In addition, since the slopes in Fig.4b are proportional to τ, the Lorentzian characteristic width of the displacement probability increases linearly with time; the rate of increase is near the turbulent velocity u_t .

[9] Thanks to P.Hennequin, A.Truc and C.Honoré

Conclusions

Different findings are worth noting from this experiment

- A calibrated measurement of the plasma form factor is possible. In this experiment it is found to be of the order of $10^7/10^9$, well above thermal equilibrium where S(k)=1.
- The form factor spectrum S(**k**) does not fit a scale law ($S \propto k^{-a}$) but rather an exponential one ($S \propto e^{-k\,lp}$.).
- The addition of a weak vertical B to the main toroidal B-field decreases the form factor intensity by one and a half order of magnitude.
- A time correlation function model, based on particle random motion concepts, can fit nicely the experimental data for given scattering k.
- When this model is fit to the experimental data, the plasma turbulent mean square velocity is coherently found.
- But, in contradiction with the particle random motion correlation model, the extracted correlation length $l_{c,}$, depends on the observation scale k. It depends in such a way as $k\, l_c \sim 1$.
- The (fluid element) lagrangian displacement probability distribution can be measured. It is found to be a gaussian function of the distance only for short times, but to be a lorentzian function for times of the order of the correlation time.